The Sequestration of CO_2

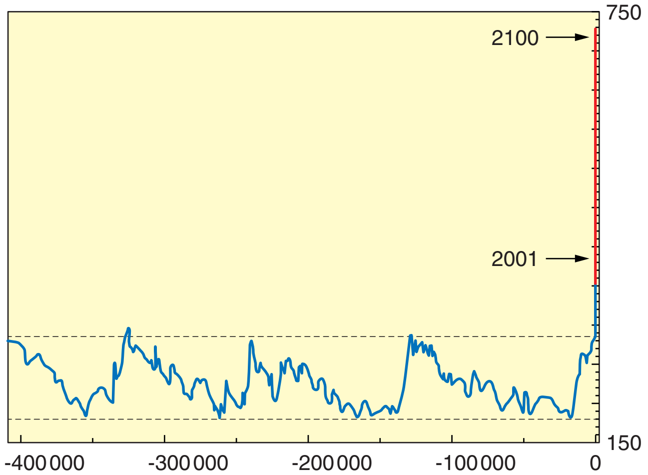
The reduction of greenhouse gas emissions, especially CO_2, represents a major technological and societal challenge in the fight against climate change. Among the measures likely to reduce anthropic CO_2 emissions, capture and geological storage holds out promise for the future.

What is at Stake

The risks associated with climate change have been the subject of much debate in recent years. Today, most experts think that these risks are real and directly linked to the emission of greenhouse gases, especially CO_2. Recent decades have witnessed a large rise in CO_2 emissions, thereby increasing the concentration of CO_2 in the atmosphere. The latter increase is thought to be responsible for the global warming trend already observed, and could have even more severe consequences unless measures are taken.

Scenarios established by the IPCC[1] (Intergovernemental Panel for Climate Change) show that the CO_2 content could rise from a current value of about 360 ppm to a value that, unless preventive measures are taken, could exceed 1000 ppm by the end of the century, representing considerable risks of climate change.

Fig. 1 Variations in the atmospheric CO_2 concentration (in ppm)



Source: IPCC

Conferences like the Rio and Johannesburg Summits and the Conferences of Parties constitute a first step towards a resolute international effort to limit GHG emissions. It was at such a conference that the **Kyoto Protocol** was drafted in 1997. It required 38 developed countries to reduce, by 5.2% on average, their levels of emissions held responsible for global warming[2]. The July 2001 agreement reached between the parties at the Bonn conference made future ratification possible. If the protocol had been ratified by Russia in 2003, it could have already come into effect.

Given this context, the European Union proposed a **Directive on emissions quota trading** that was approved on July 22, 2003. It stipulates commitments by specific manufacturers and their respective governments, relative to their GHG[3] emissions for the period 2005-2012, as well as penalties if these commitments are exceeded.

What Solutions are Possible?

The breakdown for anthropic CO_2 emissions is as follows: electricity production (39%), industry (22%) and transport (23%). To curb these emissions, three modes of action can be considered:

- The first is to reduce energy consumption, which can be controlled by modifying consumer habits and negotiating commitments per economic sector. The automotive industry is one example. European automobile manufactures undertook commitments which, in the future, should translate into a perceptible decrease in CO_2 emissions per kilometer traveled: from 190 g/km in 1997, it should drop to 160 g/km in 2003, and to 140 g/km by 2008, with a target of 120 g/km by 2012.
- The second is to introduce fuels and motor fuels that give off less CO_2 per unit of energy produced. For instance, replacing coal with natural gas in a thermal power plant will significantly reduce CO_2 emissions. Another way is to boost reliance on nuclear power and renewable energies, although each of these pathways has limitations of its own. Using biomass for fuel and biofuels can also help improve the CO_2 balance insofar as the production of biomass enables the capture of atmospheric CO_2.

(1) GIEC (Groupe international d'experts sur le climat).
(2) The French objective is to stabilize GHG emissions at the 1990 level by 2012.
(3) Greenhouse gas.

The Sequestration of CO_2

- The third mode of action, which we will examine subsequently, consists of capturing and storing CO_2 in underground geological formations. This option can be applied to fixed installations at which energy production is concentrated. It can also be applied to the production of hydrogen from fossil fuels; the hydrogen can subsequently used for decentralized applications to produce energy without CO_2 emissions.

Among these major options aimed at reducing, or even eliminating anthropic CO_2 emissions, the capture-storage pathway presents a number of advantages:

- It enables continued use of fossil carbon sources;
- For the renewable energies, it provides the time needed to bring costs down and make the necessary technology advances.

In the last few years, studies have been carried out on the geological storage of CO_2, primarily in the United States, Japan and Europe. The basic concept is to capture the CO_2 emitted by a major source (such as industrial flue gases or a raw CO_2-rich natural gas at extraction), to concentrate it and ship it to a suitable geological storage site.

CO_2 Capture and Geological Storage: a Promising Approach

Capture

The CO_2 in combustion flue-gases can be captured using existing techniques. It is an operation that requires gas scrubbing installations using solvents, especially amines like MEA (monoethanolamine), used to treat natural gas.

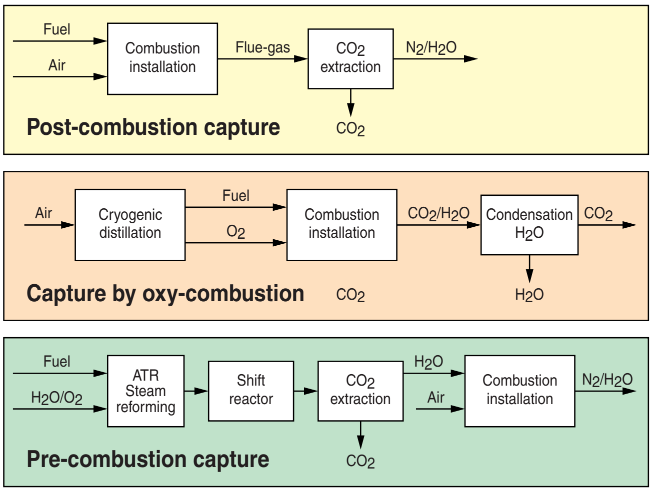
Installations equipped with gas scrubbing capability have a disadvantage: they are very space-, cost- and energy-intensive. In certain cases, the energy requirement is almost doubled. Moreover, the operating conditions are not very favorable, because they must process large volumes of low-pressure fumes containing diluted concentrations of CO_2. That's why other options are preferred when planning new installations.

Figure 2 shows the most important CO_2 capture options. For an existing installation, unless a complete overhaul is planned, only one solution can be applied directly: to install a gas scrubbing system that is well adapted to that particular installation.

For new installations, the two other options represented schematically in Figure 2 can be considered.

The fuel can be converted into synthesis gas, a mix of CO and hydrogen, either by steam reforming (natural gas) in the

Fig. 2 The main options relative to CO_2 capture



presence of water, or by partial oxidation in the presence of oxygen. The CO in the mix reacts with the water during the shift conversion stage to form CO_2 and hydrogen. Thus, the CO_2 is separated from the hydrogen under good conditions (precombustion capture) and the hydrogen can be used to produce energy (electricity or heat) without emitting CO_2.

When implementing the oxycombustion technique, combustion takes place in the presence of pure oxygen, which makes it possible to obtain combustion gases containing concentrated CO_2 that is easy to separate from the steam vapor with which it is mixed.

Geological Storage

Once the CO_2 is captured, it should be sequestered for long periods, at least throughout the time frame during which the CO_2 problem is likely to remain critical which should not exceed one or two centuries. As a precautionary measure, consideration is being given to solutions that would sequester the CO_2 for thousands of years. **In this lies the key difference between the issues associated with the geological storage of CO_2 and the storage of radioactive waste, for instance.**

Storage beneath the seabed is one option that has been explored, but it has two major disadvantages: first, its long-term outcome remains difficult to model and uncertain; secondly, not much is known about the impact of higher CO_2 concentrations on marine ecosystems.

Therefore, the preferred solution is generally onshore geological sequestration, with the following options:

- *Storage in depleted oil and gas fields*. This option is particularly interesting. In fact, when CO_2 is injected at the production stage, one can take advantage of injection to effect enhanced oil recovery. Obviously, any CO_2 escaping with the production fluids must be recovered and returned to the reservoir. The most attractive storage aspect is the natural confinement offered by such structures, which have served as oil or gas traps for several millions of years.

– *Storage in unexploited coal seams*. Coal adsorbs CO_2 preferentially instead of the methane initially present. This very interesting trapping mechanism also enables the mobilization of methane, which can be recovered in producing wells, a potentially attractive economic benefit. The key parameter associated with this storage solution is certainly the permeability of this type of formation. In general, it is very low compared to the rock holding hydrocarbon reservoirs and the kind of aquifers suitable for CO_2 storage. It might not be possible to inject large quantities of CO_2 without multiplying the number of injecting wells. Ongoing research projects should explore the real injectivity of this type of formation(4).

– *Storage in deep saline aquifers*. This solution has the greatest potential in terms of storage capacity. Due to the depth of these formations and their high salt content, they cannot be used as sources of drinking or irrigation water.

These aquifers can be open or closed. The configuration of closed aquifers(5) is identical to that of oil and gas reservoirs, which ensures effective confinement vertically and laterally. This is the type of aquifer used to store natural gas. It certainly provides a "safer" option for continental storage, but capacity is limited. Open aquifers lie on a horizontal or slightly inclined plane. That they do not ensure lateral confinement would enable CO_2 to migrate. This being said, their slow flowrate and large size would promote confinement, assuming the presence of overburden of sufficiently good quality. In this case, the main trapping mechanism is the dissolution of gas in water. The "weak point" of this solution is that little is known about the subject. This type of formation does not contain resources of interest, so they have virtually never been studied. A major characterization effort is called for, in order to qualify this type of aquifer for geological storage, especially onshore. Closed aquifers are like oil and gas reservoirs in that storage is **reversible**: stored gas (or a large part thereof) can be recovered. This cannot be said of unconfined aquifers.

Table 1 shows the CO_2 storage potential for different geological structures (IEA data). Although current estimates are hardly precise, one notes that potential storage capacity is theoretically comparable to the quantities of CO_2 emitted.

Table 1
Potential storage capacity for different storage modes

Storage options	Total capacity	
	Gt CO_2	Share of aggregate emissions in 2050 (%)
Depleted oil and gas reservoirs	920	45
Deep aquifers	400-10 000	20-500
Unexploited coal veins	40	2

Current Situation and Future Outlook

Different CO_2 sequestration operations have been carried out or are being set up. One is the Sleipner Field operation in the North Sea, where the Norwegian company Statoil recovers a million tons of CO_2 a year from natural gas and reinjects it into a saline aquifer 1,000 meters beneath the seabed. IFP is involved in monitoring this operation as part of a program supported by the European Union. IFP is also taking part in the Recopol Project studying the injection of CO_2 into veins of coal, which gave rise to a demonstration pilot operation in Poland. Currently, there are many such projects underway in Europe and elsewhere in the world.

More R&D is needed to develop new CO_2 capture and sequestration techniques that are more economical and safer. IFP is actively involved in this effort. At the national level, under the auspices of the French agency for the environment and energy management (ADEME), IFP and BRGM (French bureau for geological and mining research) are the joint leaders of Le Club CO_2, whose membership includes key parties from the industrial and research sectors. IFP is also leader for a major French project partly funded by the RTPG ("Réseau Technologique Pétrole et Gaz") in order to study storage optimization for various geological formations.

At the European level, IFP is coordinating the Castor Project involving thirty industrial and research entities to study the capture and geological sequestration of CO_2. IFP is also taking part in Encap, a project for the development of systems to produce electricity from different fuels (coal, natural gas, petroleum fuels) with the sequestration of CO_2.

Today, the main problem is cost. Capture and sequestration currently represent a minimum estimated cost of €50 per ton of CO_2 avoided. Steps must be taken to cut costs and thereby ensure the dissemination of these techniques. It will be

(4) The European project RECOPOL gave rise to a pilot system to inject $C0_2$ into coal veins in Poland. TNO is project coordinator and IFP, Air Liquide, Gaz de France and Gazonor represent France.

(5) This is the type of aquifer used for natural gas storage, notably in France.

The Sequestration of CO_2

equally vital to ensure the acceptance of the general public. The question is whether such underground storage could have impacts on the environment and two study in depth: CO_2 leak risks and potential effects on drinking water reserves, ecosystems and human population. The issues are also to develop adequate measurement and control tools and procedures for this storage type. In other respects the new European demonstration projects will be essential to validate in real conditions the CO_2 sequestration option from the industrial point of view as well as the environmental one. They will give the right and objective information for better communication with the public authorities and the customers.

In July 2003, a European Directive bearing on the implementation of an emissions trading market was approved, which should promote the launch of new operations.

Conclusion

The capture and geological sequestration of CO_2 represents a new option that could make a significant contribution to the reduction of greenhouse gas emissions in the future.

R&D programs, which need broad national, European and international cooperation, should eventually bring costs down and ensure long-term storage safety. Besides the technical aspects, public perception will be key to public acceptance of this technique.

Pierre Le Thiez
pierre.le-thiez@ifp.fr

Final text received on January 5, 2004